

International Journal of Modern Physics A
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Direct CP and T Violation in Baryonic B Decays

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We review the direct CP and T violation in the three-body baryonic B decays in the standard model. In particular, we emphasize that the direct CP violating asymmetry in $B^\pm \rightarrow p\bar{p}K^{*\pm}$ is around 22% and the direct T violating asymmetry in $\bar{B}^0 \rightarrow \Lambda\bar{p}\pi^+$ can be as large as 12%, which are accessible to the current B factories at KEK and SLAC as well as SuperB and LHCb.

Keywords: CP and T violation; B meson decays; Baryonic modes.

Direct CP violation has been measured in both K^0 and B^0 systems¹, but it has not been observed and conclusive in K^\pm and B^\pm systems¹, respectively. On the other hand, T violation has been only seen in the K^0 process¹, related to the indirect CP violating parameter ϵ_K , whereas no T violating effect has been found in either K^\pm or B systems yet. In the standard model (SM), it is clear that the unique phase of the Cabbibo-Kobayashi-Maskawa (CKM) matrix² is responsible for both observed CP and T violating effects. In this talk, we would like to explore the possibility to detect the direct CP and T violation in the B systems in the current B -factories as well as the future ones such as SuperB and LHCb. In particular, we concentrate on the three-body charmless baryonic processes. Our goal of the talk is to test the CKM paradigm of CP violation and unfold new physics.

In the framework of local quantum field theories, T -violation implies CP -violation (and vice versa), because of the CPT invariance of such theories. Moreover, no violation of CPT symmetry has been found¹. Still, it will be worthwhile to remember that outside this framework of local quantum field theories, there is no reason for the two symmetries to be linked³. Therefore, it would be interesting to directly investigate T violation in B decays, rather than inferring it as a consequence of CP -violation. The characteristic observables of the direct CP and T violation are rate asymmetries and momentum correlations, respectively. For example, in (conjugate) processes such as $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M$ ($\bar{B} \rightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M}$), the direct CP asymmetry arises if both the weak (γ) and strong (δ) phases are non-vanishing, given by

$$A_{CP} = \frac{\Gamma(B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M) - \Gamma(\bar{B} \rightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M})}{\Gamma(B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M) + \Gamma(\bar{B} \rightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M})} \propto \sin \gamma \sin \delta, \quad (1)$$

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whereas the direct T violation is related to the correlations known as triple product correlations (TPC's), such as $\vec{s}_B \cdot (\vec{p}_B \times \vec{p}_M)$, given by

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T) \propto \sin \gamma \cos \delta. \quad (2)$$

where ⁴

$$A_T = \frac{\Gamma(\vec{s}_B \cdot (\vec{p}_B \times \vec{p}_M) > 0) - \Gamma(\vec{s}_B \cdot (\vec{p}_B \times \vec{p}_M) < 0)}{\Gamma(\vec{s}_B \cdot (\vec{p}_B \times \vec{p}_M) > 0) + \Gamma(\vec{s}_B \cdot (\vec{p}_B \times \vec{p}_M) < 0)}, \quad (3)$$

and \bar{A}_T is the corresponding asymmetry of the conjugate process. It is interesting to note that to have a non-zero value of A_{CP} , both weak and strong phases are needed, whereas in the vanishing limit of the strong phase, \mathcal{A}_T is maximal. Furthermore, there is no contribution ⁴ to \mathcal{A}_T from final state interaction due to electromagnetic interaction.

From the effective Hamiltonian at the quark level for B decays ⁵, the amplitudes of $B^- \rightarrow p\bar{p}K^-$ and $B^- \rightarrow p\bar{p}K^{*-}$ are approximately given by ^{6,7,8,9}

$$\begin{aligned} \mathcal{A}_K &\simeq i \frac{G_F}{\sqrt{2}} m_b f_K \left[\alpha_K \langle p\bar{p} | \bar{u}b | B^- \rangle + \beta_K \langle p\bar{p} | \bar{u}\gamma_5 b | B^- \rangle \right], \\ \mathcal{A}_{K^*} &\simeq \frac{G_F}{\sqrt{2}} m_{K^*} f_{K^*} \varepsilon^\mu \alpha_{K^*} \langle p\bar{p} | \bar{u}\gamma_\mu (1 - \gamma_5) b | B^- \rangle, \end{aligned} \quad (4)$$

respectively, where G_F is the Fermi constant, $f_{K^{(*)}}$ is the meson decay constant, given by $\langle K^- | \bar{s}\gamma_\mu \gamma_5 u | 0 \rangle = -i f_K q_\mu$ ($\langle K^{*-} | \bar{s}\gamma_\mu u | 0 \rangle = m_{K^*} f_{K^*} \varepsilon_\mu$) with q_μ (ε_μ) being the four momentum (polarization) of K^- (K^{*-}), and $\alpha_{K^{(*)}}$ and β_K are defined by

$$\begin{aligned} \alpha_K(\beta_K) &\equiv V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* \left[a_4 \pm a_6 \frac{2m_K^2}{m_b m_s} \right], \\ \alpha_{K^*} &\equiv V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* a_4, \end{aligned} \quad (5)$$

where V_{ij} are the CKM matrix elements and a_i ($i = 1, 4, 6$) are given by

$$a_1 = c_1^{eff} + \frac{1}{N_c} c_2^{eff}, \quad a_4 = c_4^{eff} + \frac{1}{N_c} c_3^{eff}, \quad a_6 = c_6^{eff} + \frac{1}{N_c} c_5^{eff}, \quad (6)$$

with c_i^{eff} ($i = 1, 2, \dots, 6$) being effective Wilson coefficients (WC's) shown in Ref. ⁵ and N_c the color number for the color-octet terms. We note that for the decay amplitudes in Eq. (4) we have neglected the small contributions ^{8,9} from $\langle p\bar{p} | J_1 | 0 \rangle \langle K^{(*)} | J_2 | B \rangle$ involving the *vacuum* $\rightarrow p\bar{p}$ time-like baryonic form factors ¹⁰, where $J_{1,2}$ can be (axial-)vector or (pseudo)scalar currents. However, in our numerical analysis we will keep all amplitudes including the ones neglected in Eq. (4). Numerically, the CKM parameters are taken to be ¹ $V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$ and $V_{tb}V_{ts}^* = -A\lambda^2$ with $A = 0.818$, $\lambda = 0.2272$, the values of (ρ, η) are $(0.221, 0.340)$ ¹. We remark that a_i contain both weak and strong phases, induced by η and quark-loop rescatterings. Explicitly, at the scale m_b and $N_c=3$, we obtain a set of a_1 , a_4 ,

and a_6 as follows:

$$\begin{aligned} a_1 &= 1.05, \\ a_4 &= [(-427.8 \mp 9.1\eta - 3.9\rho) + i(-83.2 \pm 3.9\eta - 9.1\rho)] \times 10^{-4}, \\ a_6 &= [(-595.5 \mp 9.1\eta - 3.9\rho) + i(-83.2 \pm 3.9\eta - 9.1\rho)] \times 10^{-4}, \end{aligned} \quad (7)$$

for the $b \rightarrow s$ ($\bar{b} \rightarrow \bar{s}$) transition.

From Eq. (4), we derive the simple results for the direct CP asymmetries of the $K^{(*)}$ modes as follows:

$$A_{CP}(K^{(*)}) \simeq \frac{|\alpha_{K^{(*)}}|^2 - |\bar{\alpha}_{K^{(*)}}|^2}{|\alpha_{K^{(*)}}|^2 + |\bar{\alpha}_{K^{(*)}}|^2}, \quad (8)$$

where $\bar{\alpha}_{K^{(*)}}$ denote the values of the corresponding antiparticles. It is easy to see that $A_{CP}(K^{(*)})$ are independent of the phase spaces as well as the hadronic matrix elements. As a result, the hadron parts along with their uncertainties in $A_{CP}(K^{(*)})$ are divided out in Eq. (8). We note that the CP asymmetries in Eq. (8) are related to the weak phase of $\gamma(\phi_3)$ ¹.

Our results on the direct CP violation are summarized in Table 1. In the table,

Table 1. Direct CP asymmetries in $B \rightarrow p\bar{p}M$.

$A_{CP}(M)$	$A_{CP}(K^{*\pm})$	$A_{CP}(K^\pm)$	$A_{CP}(K^{*0})$	$A_{CP}(\pi^\pm)$
Our work ⁹	0.22	0.06	0.01	-0.06
BaBar ¹¹	0.32 ± 0.14	$-0.13^{+0.09}_{-0.08}$	0.11 ± 0.14	0.04 ± 0.08
Belle ¹²		-0.02 ± 0.05		-0.17 ± 0.10

we have included the current experimental data as well as the decay modes of $B^\pm \rightarrow p\bar{p}\pi^\pm$. We note that the possible fluctuations induced from non-factorizable effects, time-like baryonic form factors and CKM matrix elements for $A_{CP}(K^{(*)})$ are about 0.01 (0.04), 0.003 (0.01) and 0.01 (0.01), respectively. The uncertainties from time-like baryonic form factors are constrained by the data of $\bar{B}^0 \rightarrow n\bar{p}D^{*+}$ and $\bar{B}^0 \rightarrow \Lambda\bar{p}\pi^+$ ¹⁰ and the errors on the CKM elements are from ρ and η given in Ref.¹. It is interesting to point out that the large value of $A_{CP}(B^\pm \rightarrow p\bar{p}K^{*\pm})=22\%$ is in agreement with the BABAR data of $(32 \pm 14)\%$. However, taken at face value; the sign of our prediction $A_{CP}(B^\pm \rightarrow p\bar{p}K^\pm)$ is different from those by BABAR¹¹ and BELLE¹² Collaborations. Since the uncertainties of both experiments are still large it is too early to make a firm conclusion.

For the direct T violation in the three-body charmless baryonic B decays¹³, we concentrate on $\bar{B}^0 \rightarrow \Lambda\bar{p}\pi^+$ by looking for the TPC of the type $\vec{s}_\Lambda \cdot (\vec{p}_{\bar{p}} \times \vec{p}_\Lambda)$. It is interesting to note that¹⁴:

$$Br(B^0 \rightarrow \Lambda\bar{p}\pi^-) = (3.29 \pm 0.47) \times 10^{-6} \gg Br(B^- \rightarrow \Lambda\bar{p}) < 4.6 \times 10^{-7}. \quad (9)$$

The enhancement of three-body decay over the two-body one is due to the reduced energy release in B to π transition by the fastly recoiling π meson that favors

the dibaryon production¹⁵. Theoretical estimations baryonic B decays are made^{7,16,17}, in consistent with the experimental observations.

In the factorization method, the decay amplitude of $\bar{B}^0 \rightarrow \Lambda \bar{p} \pi^+$ contains the $\bar{B}^0 \rightarrow \pi^+$ transition and $\Lambda \bar{p}$ baryon-pair inducing from the vacuum. The contributions to the decay at the quark level are mainly from O_1 , O_4 and O_6 operators. From these operators and the factorization approximation, the decay amplitude is given by^{13,16}

$$\begin{aligned} M &= M_1 + M_4 + M_6, \\ M_i &= \frac{G_f}{\sqrt{2}} \lambda_i a_i \langle \pi^+ | \bar{u} \gamma^\mu (1 - \gamma_5) b | \bar{B}^0 \rangle \langle \Lambda \bar{p} | \bar{s} \gamma_\mu (1 - \gamma_5) u | 0 \rangle, \quad (i = 1, 4), \\ M_6 &= \frac{G_f}{\sqrt{2}} V_{tb} V_{ts}^* 2a_6 \langle \pi^+ | \bar{u} \gamma^\mu (1 - \gamma_5) b | \bar{B}^0 \rangle \frac{(p_\Lambda + p_{\bar{p}})_\mu}{m_b - m_u} \langle \Lambda \bar{p} | \bar{s} (1 + \gamma_5) u | 0 \rangle, \quad (10) \end{aligned}$$

where $\lambda_1 = V_{ub} V_{us}^*$, $\lambda_4 = -V_{tb} V_{ts}^*$ and a_i are defined in Eq. (6). From Eq. (10), the T-odd transverse polarization asymmetry P_T is found to be

$$P_T \propto \left(V \cdot S - A \cdot P \right) \text{Im} (V_{ub} V_{us}^* V_{tb} V_{ts}^* a_1 a_6^*), \quad (11)$$

where S, P, V and A are combinations of form factors, given by¹³

$$\begin{aligned} V &= F_1^{B \rightarrow \pi}(t) [F_1(t) + F_2(t)], \quad A = F_1^{B \rightarrow \pi}(t) g_A(t), \\ S &= \frac{m_B^2 - m_\pi^2}{m_b - m_u} F_0^{B \rightarrow \pi}(t) f_S(t), \quad P = \frac{m_B^2 - m_\pi^2}{m_b - m_u} F_0^{B \rightarrow \pi}(t) g_P(t). \quad (12) \end{aligned}$$

It is noted that the $V \cdot S$ ($A \cdot P$) term is from vector-scalar (axialvector-pseudoscalar) interference and there is no T-odd term from $\text{Re}(M_1 M_4^\dagger)$ due to the same current structures. In Eq. (12), $F_{1,0}^{B \rightarrow \pi}(t)$ are the well known mesonic $\bar{B}^0 \rightarrow \pi^+$ transition form factors¹⁸, while $F_{1,2}(t)$, $g_A(t)$, $h_A(t)$, $f_S(t)$ and $g_P(t)$ are the $0 \rightarrow \Lambda \bar{p}$ time-like baryonic form factors, defined in Ref.¹³. Based on the QCD counting rules¹⁹ and $SU(3)$ flavor symmetry, at $t \rightarrow \infty$ one has that

$$F_1(t) + F_2(t) \sim g_A(t) \sim h_A(t) \sim f_S(t) \sim g_P(t) \sim \frac{C}{t^2}. \quad (13)$$

In this limit $A_T \rightarrow 0$ and thus no T violation is expected. However, at the finite t there are some high power terms of the t expansion. A simple scenario of the power expansions for the baryonic form factors is as follows:²¹

$$\begin{aligned} F_1(t) + F_2(t) &= \left(\frac{C}{t^2} + \frac{D}{t^3} \right) \left[\ln \left(\frac{t}{\Lambda_0^2} \right) \right]^{-\gamma}, \quad g_A(t) = \left(\frac{C}{t^2} \right) \left[\ln \left(\frac{t}{\Lambda_0^2} \right) \right]^{-\gamma}, \\ f_S(t) &= n_q \left(\frac{C}{t^2} + \frac{D}{t^3} \right) \left[\ln \left(\frac{t}{\Lambda_0^2} \right) \right]^{-\gamma}, \quad g_P(t) = n_q \left(\frac{C}{t^2} \right) \left[\ln \left(\frac{t}{\Lambda_0^2} \right) \right]^{-\gamma}, \quad (14) \end{aligned}$$

where $n_q = (m_\Lambda - m_p)/(m_s - m_u)$, $\gamma = 2.148$ and $\Lambda_0 = 300 \text{ MeV}$ and C and D are two new form factors.

We now evaluate the numerical values for the TPCs in this simple power expansion scenario in Eq. (14). Our results of A_T (\bar{A}_T) and $\mathcal{A}_T = (A_T - \bar{A}_T)/2$ are shown

Table 2. Triple product correlation asymmetries (in percent) of A_T (\bar{A}_T) for $\bar{B}^0 \rightarrow \Lambda \bar{p} \pi^+$ ($B^0 \rightarrow \bar{\Lambda} p \pi^-$) and $\mathcal{A}_T = (A_T - \bar{A}_T)/2$.

$A_T, \bar{A}_T, \mathcal{A}_T$	$\gamma = 57^\circ$	$\gamma = 0^\circ$
$\delta \neq 0$	12.0, -8.4, 10.2	2.0, 2.0, 0
$\delta = 0$	10.4, -10.4, 10.4	0, 0, 0

in Table 2. As an illustration, in the table we have also turned off the strong phase ($\delta = 0$) by taking the imaginary parts of the quark-loop rescattering effects to be zero. From the table, we see explicitly that \mathcal{A}_T is indeed nonzero and maximal in the absence of the strong phase. We note that in our calculations we have neglected the final state interactions due to electromagnetic and strong interactions, which are believed to be small in three-body charmless baryonic decays ^{7,20}. We also note that $A_{CP} \sim 1.1\%$ in $\bar{B}^0(B^0) \rightarrow \Lambda \bar{p} \pi^\pm$ can be induced but it is too small to be measured. It is interesting to point out that in order to observe A_T (\bar{A}_T) in $\bar{B}^0 \rightarrow \Lambda \bar{p} \pi^+$ ($B^0 \rightarrow \bar{\Lambda} p \pi^-$) being at $12 - 8\%$, we need to have about $(1 - 2) \times 10^8$ $B\bar{B}$ pairs at 2σ level. This is within the reach of the present day B factories at KEK and SLAC and others that would come up. It is clear that an experimental measurement of \mathcal{A}_T is a reliable test of the CKM mechanism of CP violation and, moreover, it could be the first evidence of the direct T violation in B decays. Finally, we remark that we have also explored the direct CP and T violation in $B \rightarrow \Lambda \bar{\Lambda} K$ ⁷ and we have found that the direct CP violating effect is small but the T violating one is as large as that in $B \rightarrow \Lambda \bar{p} \pi$.

In summary, we have shown that the direct CP violating asymmetry in $B^\pm \rightarrow p \bar{p} K^{*\pm}$ is around 22% and the direct T violating asymmetry in $\bar{B}^0 \rightarrow \Lambda \bar{p} \pi^+$ can be as large as 12%, which are accessible to the current B factories at KEK and SLAC as well as the future ones such as SuperB and LHCb.

Acknowledgements

This work is financially supported by the National Science Council of Republic of China under the contract #: NSC-95-2112-M-007-059-MY3.

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